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The goal of the work described in this report is to provide a better wingsuit, specifically one that allows for greater flight distance, for use in military and extreme sports circles. Many current wingsuits are at their aerodynamic limit due to poor performance from the fabric that makes them up. We propose to evaluate the benefit of adding a rigid wing to the wingsuit, using rapid prototyping in a 3D printer and non-dimensional wind tunnel analysis.

Designing a High-Lift Performance Wingsuit

FL2015 Senior Design
Wingsuit Project

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1 Introduction

1.1 Project problem statement

The initial goal of the project was to design a high-performance wingsuit, specifically, a wingsuit that offered better lifting performance than current-generation models. The only constraint placed on our group at the outset was to arrive at a robust and consistent definition of the term “wingsuit.” We arrived at the conclusion that a wingsuit is a personal flight device that allows a skydiver or BASE jumper to travel a significant horizontal distance during his or her descent, all the while transferring aerodynamic forces directly to the pilot’s body and not to any supportive structure, mechanical or otherwise.

To summarize, the current state of wingsuit flight has stagnated due to limitations on both material choices for the suit and availability of testing resources to dedicate to the extreme sports sector. Extreme or adventure sports have always been innovated upon through a slow, iterative and organic process, without the systematic hypothesizing and testing found in the mechanical engineering field.

We thus propose to conduct a thorough study of a potential wingsuit design for improving lift performance, centered on a test of a scaled-down rapidly prototyped model in the Wash U Fluid Mechanics Laboratory Wind Tunnel. The wind tunnel is only of 12” span, which severely limits the complexity of the prototype we can test, however we hope that we can produce a range of scalable test data regardless.

1.2 List of team members

The team for this project consisted of Kimon Stephanopoulos, Ben Levy, and Ignacio Rabadan. We would like to give special thanks to Ethan Glassman, who helped us iron out some kinks in our design so that it would be ready for 3D printing, and to Professors Boyd, Bulfin, Malast and Meacham for their attempts to figure out how to collect test data from the new wind tunnel.

2 Background Information Study

2.1 A short design brief description that defines and describes the design problem

The design problem itself revolves around developing a prototype that is capable of providing high lift at the extreme angles of attack that wingsuits commonly encounter. Given current data on wingsuit flight, a consistent angle of attack of 20 to 30 degrees during flight is to be expected, meaning we must be sure that our wing design is stall-resistant as well as high-lifting. Furthermore, the wing must be designed with a precisely machined mount to correspond to the wind tunnel balance. From a testing perspective, we must be sure to address the problem of modeling the human form in an accurate but repeatable manner, should further studies wish to expand upon this work.

2.2 Summary of relevant background information (such as similar existing devices or patents, patent numbers, URL's, et cetera)

Unfortunately, there is little to no formal data or technical information regarding wingsuit flight out there. Aside from various studies conducted mostly by curious students at high-level technical universities (all of which will be attached in our references), the world of wingsuit flying is still in its early stages, and most development has happened as a result of minor modifications to the original fabric design, established before the turn of the century.

What is known is that, as stated above, to be considered a wingsuit, a personal flight device must allow a skydiver or BASE jumper to travel a significant horizontal distance during his or her descent, all the while transferring aerodynamic forces directly to the pilot's body and not to any supportive structure, mechanical or otherwise. By researching on wingsuit forums and in references that address the problem of unpowered personal flight, one is able to determine a number of critical parameters for wingsuit design. These are more fully elucidated in the Concept Selection section below, but it is sufficient here to note that the most important measure of wingsuit performance is glide ratio. Glide ratio, put plainly, is a measurement of horizontal distance traveled over vertical distance traveled. Empirical evidence dictates that the common wingsuit glide ratios for the current generation hover around 2.5:1 (meaning a horizontal distance traveled 2.5 times the magnitude of the corresponding vertical distance traveled), with glide ratios of 4:1 being attainable by highly skilled pilots wearing top-of-the-line suits. When the wingsuit is flown in still air at a constant speed, the glide ratio is numerically equivalent to the lift-to-drag ratio of the wingsuit.

The most important design limitation on current wingsuits seems to be the fabric itself. While a litany of modifications to the original design have by now become standard, it is evident that any flexible fabric is aerodynamically inefficient. Fluttering fabric propagates large losses and creates massive drag due to its inherent inability to maintain a rigid lifting profile. We will thus

be exploring rigid and semi-rigid design concepts to test. It is hoped that the addition of rigidity into the lifting element of the wingsuit will improve its aerodynamic performance.

3 Concept Design and Specification

3.1 User needs, metrics, and quantified needs equations. This will include three main parts:

3.1.1 Record of the user needs interview

| Customer Data: High-Lift Wingsuit | | | |
|---|---|---|------------|
| Customer: Drs. <u>Jakiela</u> , Malast | | | |
| Address: Washington University | | Date: 11 September 2015 | |
| Question | Customer Statement | Interpreted Need | Importance |
| Are we expected to produce a full-size wingsuit or is a model satisfactory? | A model is satisfactory to produce design standards for a high-lift wingsuit | Wingsuit need not be life-size, can instead be model. Size necessary for good test data ~1-2ft wingspan | 5 |
| How will wingsuit test data be recorded? | The majority of the data to be analyzed will be obtained from wind tunnel testing. | Design must fit in a wind tunnel closely available or a wind wall to be constructed. Consider reducing model size to ~1ft span | 4 |
| What safety parameters should we keep in mind? | Safety is not a primary concern. However, consider leaving space in the assembly for a parachute rig. Also keep in mind the necessity of firmly attaching the wing to the pilot | Design must include space for (and simulated weight of) parachute system, and ideally does not hinder the pulling of the parachute cord | 3 |
| What material considerations are present? | As this is a passive flight system, weight must be minimal in order to maximize flight time. Stiffness-to-weight is therefore critical | Wing is extremely light while maintaining stiffness necessary for lift performance | 3 |

| | | | |
|--|---|---|---|
| How much of an improvement in glide ratio (and thus lift) should we aim for? | Just make it better. To be influential, the design must prove substantial aerodynamic improvement | The wingsuit must provide lift performance suitable for a glide ratio of >3:1 (ideally 5:1 or above) | 5 |
| Is a high-lift or high-speed design preferred? | These are both important. Consider the relationship between the two. Aspect ratio must be high for low-speed lift but flow should not separate. | The wingsuit must have a moderate-to-high aspect ratio wing that remains capable of producing lift at high angles of attack experienced by wingsuit jumpers | 4 |
| Are active flight control capabilities (pitch, roll, yaw) desired? | If control surfaces can be implemented, go for it. | The wingsuit may have a number of control surfaces to enhance flight performance | 2 |

Table 1. A record of our User Needs Interview with Drs. Jakiela, Malast on 9/11/15

3.1.2 List of identified metrics

| Identified User Needs: High-Lift Wingsuit | | |
|---|--|------------|
| Need Number | Need | Importance |
| 1 | Wingsuit is small enough to be tested in wind tunnel, but not too small to offer good data scalability – consider 1-2ft wingspan | 5 |
| 2 | Wingsuit is light but rigid, not exceeding 25% of the weight of the pilot | 3 |
| 3 | Wingsuit allows space for and simulates weight of parachute system, including integration of parachute ripcord | 3 |
| 4 | Wingsuit must produce high lift, increasing potential glide ratio to >5:1 | 5 |
| 5 | Wingsuit must have optimal aspect ratio for high lift while keeping flow attached | 4 |
| 6 | Wingsuit must include a number of active flight | 2 |

| | | |
|--|------------------|--|
| | control surfaces | |
|--|------------------|--|

Table 2: Identified User Needs from Interview recorded above

| Design Metrics: High-Lift Wingsuit | | | | | |
|---|------------------|------------------------|-----------------|-----------|-----------|
| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value |
| 1 | 1,4,5 | Wingspan | cm | 30 | 60 |
| 2 | 2 | Weight | kg | 0.5 | 1 |
| 3 | 3 | Parachute Space (Area) | cm ² | 20 | 40 |
| 4 | 4 | Glide Ratio | Integer | 4:1 | 10:1 |
| 5 | 5 | Aspect Ratio | Integer | 4 | 20 |
| 6 | 4,5 | Surface Area | cm ² | 250 | 500 |
| 7 | 2,6 | Control Surfaces | Integer | 0 | 3 |

Table 3: Identified Design Metrics from Interview recorded above

3.1.3 Table/list of quantified needs equations

For the table of quantified needs equations, see the Excel spreadsheet attached in “Concept Scoring,” Section 3.3.1 below.

3.2 Four (4) concept drawings

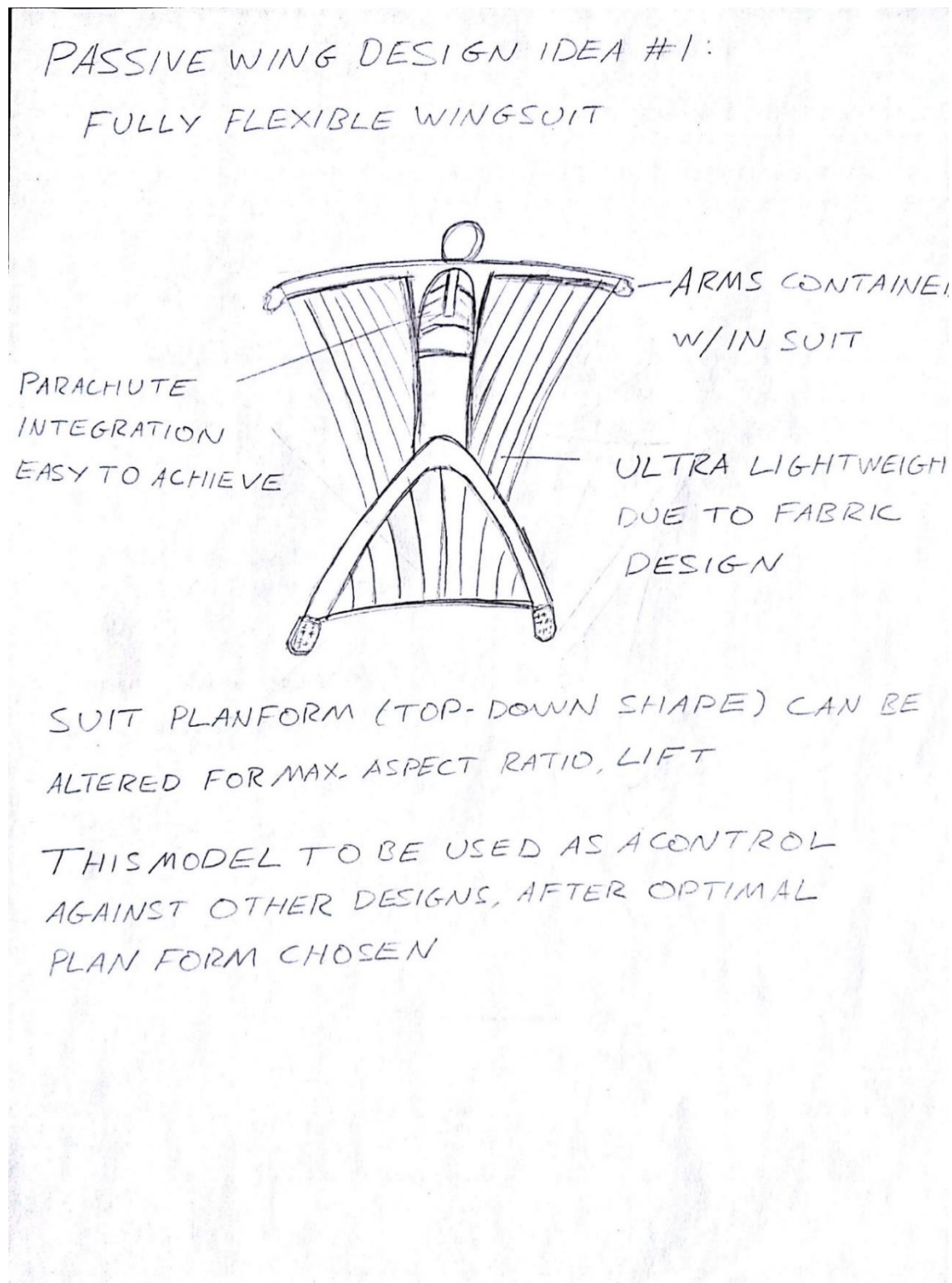


Figure 1: Concept Sketch of Full Fabric Wingsuit

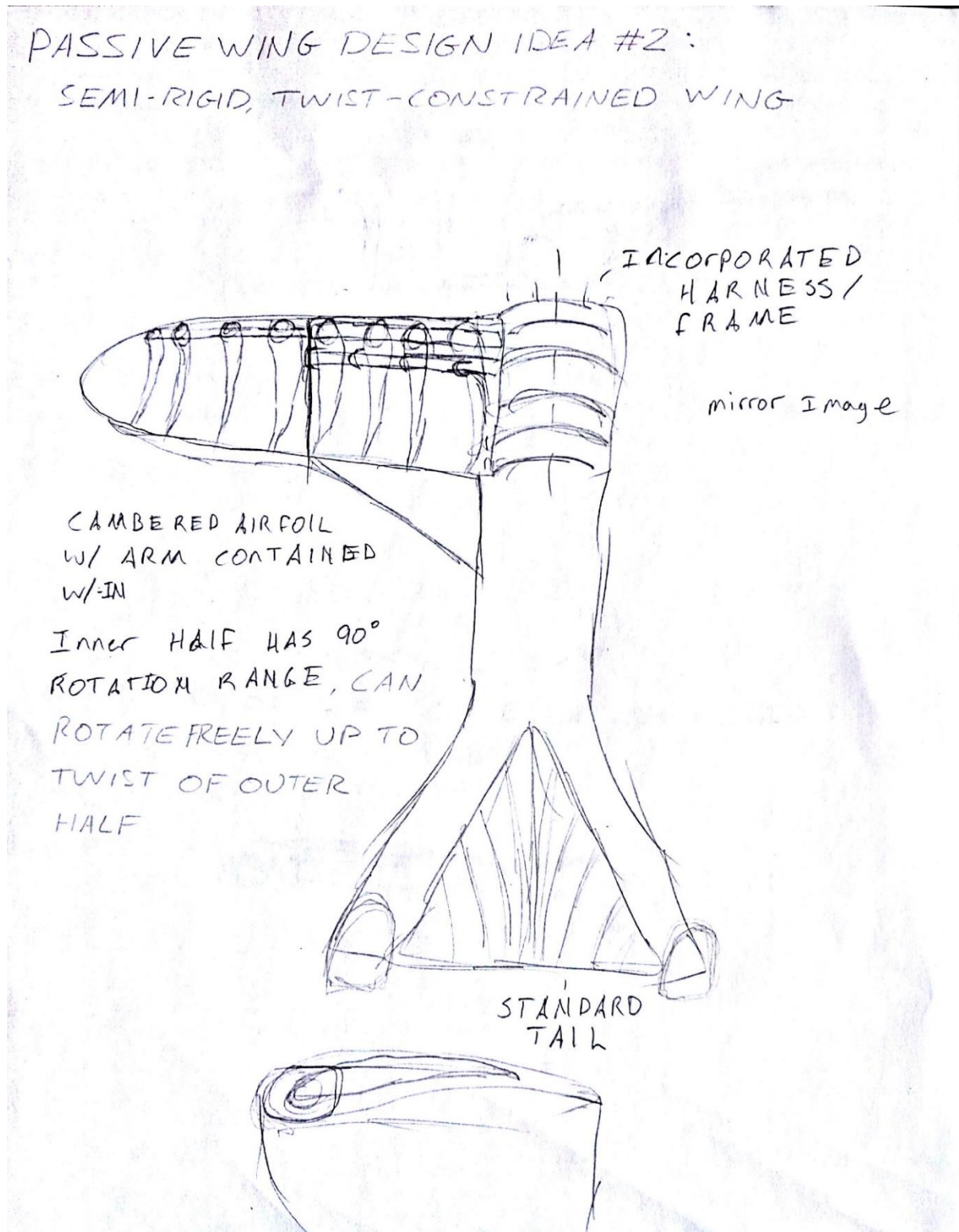


Figure 2: Concept sketch of Semi-Rigid Airfoil with Passive Twist Capability

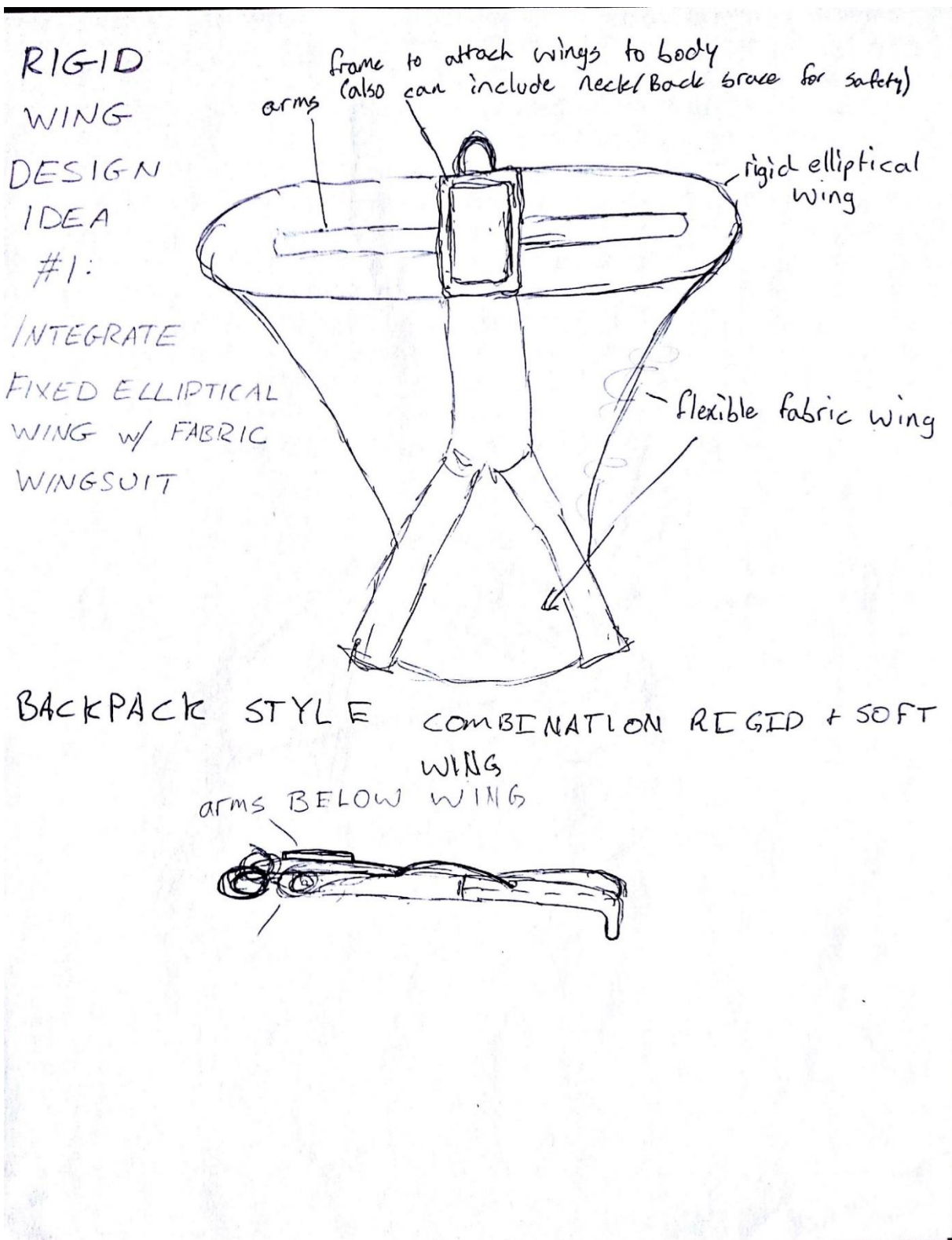


Figure 3: Concept Sketch of Rigid Elliptical Wing Design with Included Wingsuit Fabric

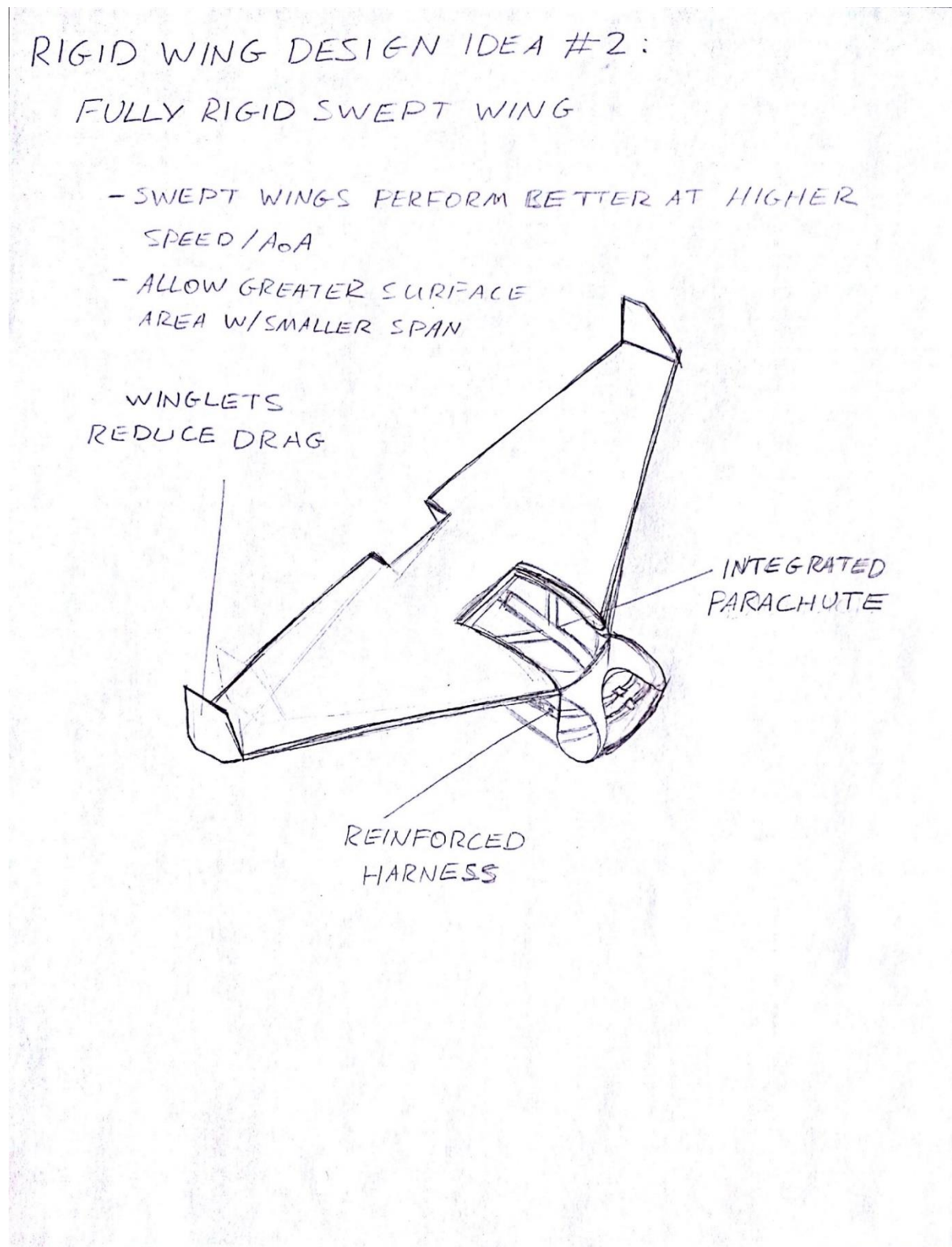


Figure 4: Concept Sketch of Fully Rigid Delta Wing Design

3.3 A concept selection process. This will have three parts:

3.3.1 Concept scoring (not screening)

See the Excel spreadsheet attached below for scoring of all 4 wingsuit concepts.

3.3.2 Preliminary analysis of each concept's physical feasibility

Concept 1: The Standard, Fully Flexible Wingsuit

This is not a difficult concept to fabricate. Multiple design plans and more-than-enough design inspiration already exists to make this happen. However, as far as fabrication goes, our limited experience with sewing and the necessity of making the suit conform to a model pilot as opposed to a real human may pose problems.

Despite this, the standard wingsuit is a proven passive flight device and allows a greater degree of aerodynamic energy retention than your standard skydiver's nylon body suit. It allows for fine control inputs from the body, with tiny arm and leg movements able to alter wing shape and change heading/pitch angle/etc. This allows experience pilots the ability to maneuver even in unpredictable winds, and the familiarity of the wingsuit community with this standard design must not be overlooked in a project such as ours.

However, as a result of making up the aerodynamic surfaces of passively fluttering nylon, this wingsuit is unsuitable for sustained flight. I would personally be hard-pressed to call wingsuit jumps "flying" per se, as it is hindered by the aerodynamic losses propagated in the suit. The wingsuit community's approach to high-lift design has been centered around adding more surface area, while we feel this is too derivative and we are already too close to the limit of these designs to make improvements in this simple way. A more fundamental redesign is necessary.

Concept 2: The Semi-Rigid Wing/Tail Web Combination

Our second concept is a derivative of the standard wingsuit design that implements rigidity in the wing to create and maintain high lift. This is accomplished by constructing a nylon wing surface closely fitted to airfoil "ribs" that give the wing chordwise stiffness. This is already a major improvement to the aerodynamic efficiency of the wingsuit design. Airfoil ribs could be designed to taper in length towards the wingtip, creating a trailing edge extension that may function like aircraft flaps to produce added lift.

This concept would be markedly harder to create, as it combines the challenge of tailoring the suit to our model pilot while maintaining the rigid wing structure. To accommodate the elbow joint in the wing, it would be necessary to implement some sort of joint around half-span, where the wing could crumple in case of the pilot needing to bend his arms. Another issue with this concept is that the

pilot's arm is the spar of the wing, resulting in massive aerodynamic loading straight to the shoulders, biceps and pectoral muscles in a live pilot. This is obviously unsavory and must be mitigated in some way with a rigid support structure for the airfoil ribs extending out from a strong harness. This harness design would in turn add weight and complexity. But the added benefit of a harness-integrated spar is that of extending the wingspan past the armspan of the pilot.

Material selection will be quite a challenge should this concept be chosen – constraining the wing twist may be accomplished by mechanical means or by choosing a material with an appropriate stiffness. Of the four designs, this may be the most challenging by the nature of the semi-rigid wing design and necessity to alleviate aerodynamic loading on the body.

Concept 3: The Rigid Elliptical Wing

The rigid elliptical wing is perhaps the perfect wing planform from classical aerodynamics. It offers a uniform lift distribution across the span, high aspect ratio, and across-the-board predictable performance. We have chosen to try and translate this wing design onto a body-mounted wingsuit.

Our design incorporates a rigid elliptical wing fitted to the pilot's body by way of a strong (metal-reinforced) harness. The rigid wing would have an almost perfectly elliptical planform and extend significantly past the pilot's own wingspan. This would offer extremely high lift performance without the need for much material. We have chosen to assess the idea of integrating the elliptical suit with nylon fabric from the wingtips to the thigh for added lift and greater control stability.

Challenges of the rigid elliptical wing include airfoil cross-section selection, fabric integration and proper mounting to the pilot's body. For modeling purposes, the harness may be polymer-based, however metal reinforcements would be recommended for such a high-lift device in a life-size implementation. It will also be challenging to achieve a compromise between maintaining a consistent wing cross-section and allowing space for the parachute pack in this design configuration. We must be making sure that flow will remain attached as much as possible throughout the flight.

Concept 4: The Rigid Swept Wing

The swept wing, inspired by Yves Rossy's "Jetman" turbine-propelled wingsuit, is similar to the rigid elliptical wing but offers increased lift performance at higher speeds and angles of attack. This solves the problem of sudden stall sometimes suffered by elliptical wings, and allows a higher rate of speed during the jump, which in turn improves lift. The swept design increases aerodynamic efficiency (and decreases likelihood of a stall) but reduces the aspect ratio of the wing, which lowers lift coefficient significantly.

We have chosen to attempt to implement this independent from a fabric wingsuit, to assess the lift performance of the rigid wing in isolation. This makes fabrication of the wing quite simple, and focuses the challenge on attaching the suit to the pilot's body. Another challenge involves the inherent lack of control of a single fixed wing. Control surfaces have not been considered at this stage, but the potential for their inclusion is reflected in the concept scoring spreadsheet below.

Physically, this design would be best suited for high-altitude, high-speed jumps, offering a glide ratio certainly higher than that of a fabric wingsuit at the expense of fine control input capability.

3.3.3 Final summary

In summary, our project revolves around selecting the wingsuit with the best lifting performance. This is rather odd, as it is not strictly a mechanical design exercise, rather a concept selection exercise to be completed via a series of well-designed experiments. So, at this stage, it is difficult to declare a “winner” of the four concepts introduced. However, perhaps we can rule out some designs due to potential manufacturing difficulties.

The semi-rigid wingsuit design is by far the most challenging to fabricate. Creating the twist-constraint mechanism and implementing it in a way so as to mitigate high aerodynamic loading on the wing is quite a task, and involves good material selection, a knowledge of exact constraint design, and the ability to apply these designs to a person-mounted craft. The position of the arms within the airfoils creates some safety concerns, which, while not priority, must be reflected in our concept decision. So it is safe to say the semi-rigid wingsuit design will most likely not be fabricated.

Secondly, the fully flexible wingsuit functions best as a control against which to test our other designs. We already (albeit anecdotally) know the performance of one of these suits, and can thus compare our other designs to this build. However, the construction of a standard wingsuit model would allow more direct comparison of experimental data and thus may be beneficial.

It appears that our goal will be to distinguish between the rigid ellipse and the rigid swept-wing designs. We must produce a set of experiments that will be able to distinguish between these. Note that in the quantified needs/metrics evaluation below, the rigid swept-wing design is best suited to our project, owing to its small wingspan, high estimated glide ratio performance, and the potential to implement active flight control surfaces in the final suit.

3.4 Proposed performance measures for the design

The obvious performance measure for this project is how much lift the wingsuit produces. This can be assessed non-dimensionally in a wind tunnel or with a wind wall, by observation of the wingsuit's lift coefficient. Should we have time to gain the software expertise, this could also be assessed on ANSYS FLUENT flow solver software.

An assessment of lift performance will lead to a determination of the number that governs wingsuit performance – glide ratio. This number, essentially the slope of a wingsuit pilot's flight, denotes the capability for improved horizontal travel offered by the wingsuit. This will be assessed by a simple free-body analysis after wind tunnel testing is completed.

The final weight of the designs will also be a crucial factor. Designs too heavy for the pilot will reduce control and induce drag, and likely require a heavier parachute build to achieve proper landing.

Concept scoring spreadsheet w/ quantified needs & metrics evaluation equations

| Quantified Happiness Equations for Senior Design Wingsuit Optimizaiton Project | | Wingspan | Weight | Parachute Space | Glide Ratio | Aspect Ratio | Surface Area | Control Surfaces | Need Happiness 1 | Need Happiness 2 | Need Happiness 3 | Need Happiness 4 | Importance Weight (all entries should add up to 1) | Happiness 1 - Plain Fabric Suit | Happiness 2 - Semi-Rigid Suit | Happiness 3 - Rigid Ellipse | Happiness 4 - Rigid Swept-Wing |
|--|-------------------------------|----------|----------|-----------------|-------------|--------------|--------------|------------------|------------------|------------------|------------------|------------------|---|---------------------------------|-------------------------------|-----------------------------|--------------------------------|
| Need# | Need | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | | | | | | | | |
| 1 | Good Size for Testing | 1 | | | | | | | 0.625 | 0.25 | 0 | 0.5 | 0.25 | 0.15625 | 0.0625 | 0 | 0.125 |
| 2 | Lightweight Suit | | 0.8 | | | | | 0.2 | 0.64 | 0.666667 | 0.333333 | 0.346667 | 0.15 | 0.096 | 0.1 | 0.05 | 0.052 |
| 3 | Space for Parachute | | | 1 | | | | | 1 | 1 | 0.25 | 0.25 | 0.05 | 0.05 | 0.05 | 0.0125 | 0.0125 |
| 4 | High Lift | | | | 0.2 | 0.4 | 0.4 | | 0.573333 | 0.229074 | 0.629111 | 0.681667 | 0.3 | 0.172 | 0.068722 | 0.188733 | 0.2045 |
| 5 | Good AR w/ Minimal Separation | | | | | 0.6 | 0.4 | | 0.7025 | 0.191111 | 0.534667 | 0.64 | 0.2 | 0.1405 | 0.038222 | 0.106933 | 0.128 |
| 6 | Flight Control Surfaces | | | | | | | 1 | 0 | 0.666667 | 0.333333 | 0.666667 | 0.05 | 0 | 0.033333 | 0.016667 | 0.033333 |
| Units | | Unit 1 | Unit 2 | Unit 3 | Unit 4 | Unit 5 | Unit 6 | Unit 7 | Total Happiness | | | | | 0.61475 | 0.352778 | 0.374833 | 0.555333 |
| Best Value | | 20 | 0.25 | 40 | 10 | 1 | 500 | 3 | | | | | | | | | |
| Worst Value | | 60 | 1 | 20 | 2 | 10 | 250 | 0 | | | | | | | | | |
| Design 1 Value - Plain Fabric Suit | | 35 | 0.4 | 40 | 3 | 3.0625 | 400 | 0 | | | | | | | | | |
| Normalized Metric Happiness 1 | | 0.625 | 0.8 | 1 | 0.125 | 0.770833 | 0.6 | 0 | | | | | | | | | |
| Design 2 Value - Semi-Rigid Suit | | 50 | 0.5 | 40 | 5 | 8.333333 | 300 | 2 | | | | | | | | | |
| Normalized Metric Happiness 2 | | 0.25 | 0.666667 | 1 | 0.375 | 0.185185 | 0.2 | 0.666667 | | | | | | | | | |
| Design 3 Value - Rigid Elliptical Suit | | 60 | 0.75 | 25 | 8 | 7.5 | 480 | 1 | | | | | | | | | |
| Normalized Metric Happiness 3 | | 0 | 0.333333 | 0.25 | 0.75 | 0.277778 | 0.92 | 0.333333 | | | | | | | | | |
| Design 4 Value - Rigid Swept-Wing Suit | | 40 | 0.8 | 25 | 9 | 4 | 400 | 2 | | | | | | | | | |
| Normalized Metric Happiness 4 | | 0.5 | 0.266667 | 0.25 | 0.875 | 0.666667 | 0.6 | 0.666667 | | | | | | | | | |

Table 4: Quantified Happiness Equations and Concept Scoring

4 Embodiment and fabrication plan

4.1 Embodiment drawing

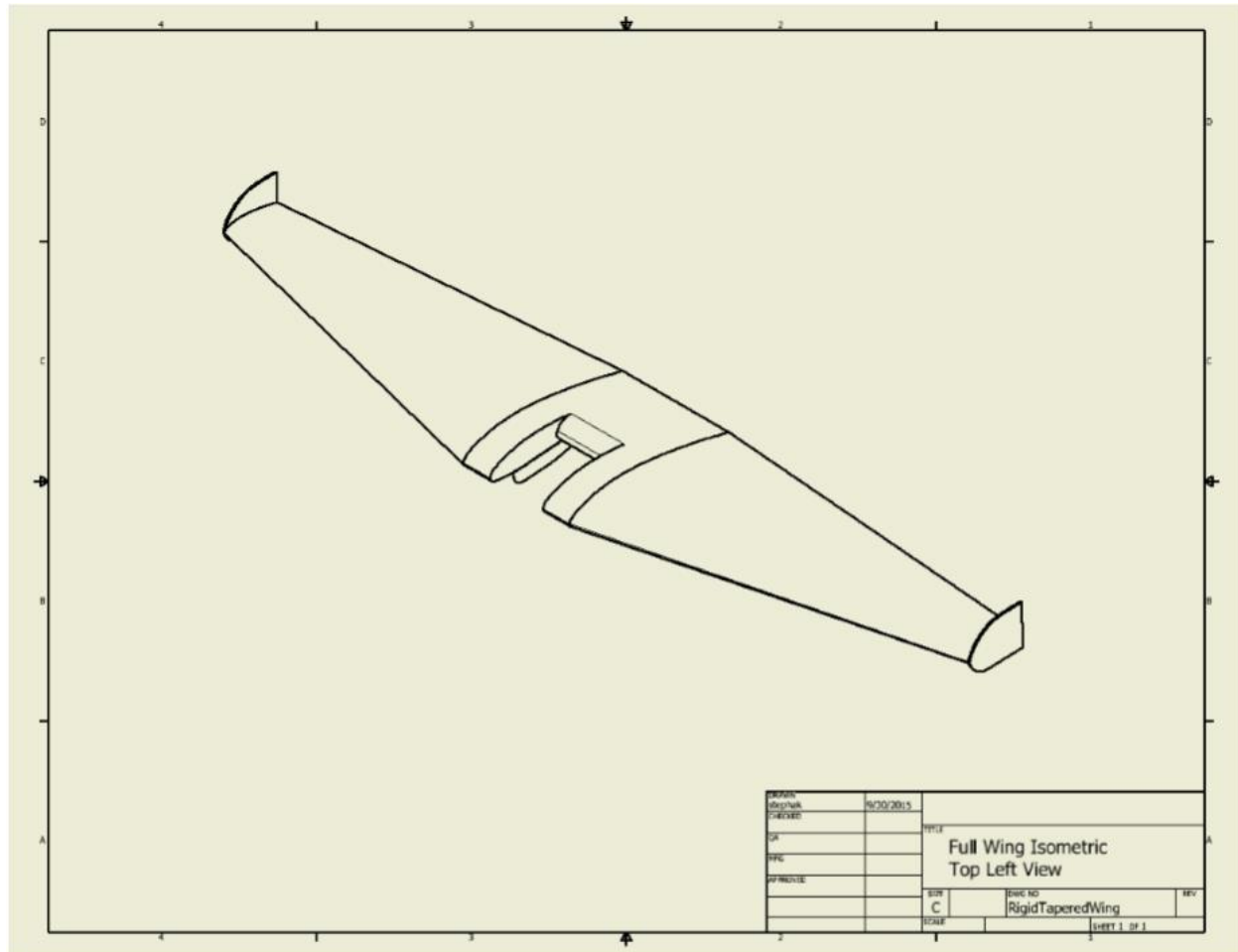


Figure 5. An initial embodiment drawing of our proposed wing design

The embodiment drawing above is atypical in that there are few mechanical interactions to consider. As such, it represents the final form of our wing. Given the difficulty of rapidly machining a wing in Wash U's student machine shop, it will be a near necessity for us to 3D print the wing. What this means is that there are few parts to display here. The mechanical elements of our prototype are limited to the aerodynamic surfaces to be attached with dowels and glue to each other and to our dummy pilot. Our choice of wing design (the long, tapered wing shown above) resulted from an initial desire to fabricate an elliptical wing, coupled with quick realizations about the difficulty of designing and manufacturing such a wing. It will be seen in the Final Drawings section below that we later transitioned to a delta wing, which offered similar ease of manufacturing along with greater stall resistance.

4.2 Parts List

| | <i>Part</i> | <i>Source</i> | <i>Supplier Part Number</i> | <i>Color, TPI, other part IDs</i> | <i>Unit price</i> | <i>Tax (\$0.00 if tax exemption applied)</i> | <i>Shipping</i> | <i>Quantity</i> | <i>Total price</i> |
|---------------|------------------------|---------------|-----------------------------|-----------------------------------|-------------------|--|-----------------|-----------------|--------------------|
| 1 | Steel Rope | McMaster | 3440T55 | 3/16" 10ft | \$11.80 | \$0.00 | \$0.00 | 1 | \$11.80 |
| 2 | Compression Sleeve | McMaster | 3897T7 | 3/16" 15/16"-10pack | \$11.18 | \$0.00 | \$0.00 | 1 | \$11.18 |
| 3 | Locite Plastic Epoxy | Home Depot | 234058 | .85 fl oz | \$5.47 | \$0.00 | \$0.00 | 3 | \$5.47 |
| 4 | Mannequin | Amazon | | 5.5" | \$8.99 | \$0.00 | \$0.00 | 2 | \$19.98 |
| 5 | Moxie Girz doll | Target | 86141478 | Doll | \$2.99 | \$0.00 | \$0.00 | 1 | \$2.99 |
| 6 | Barbie Doll | Target | 86060678 | Miniature doll | \$6.99 | \$0.00 | \$0.00 | 1 | \$6.99 |
| 7 | PLA (plastic for wing) | WUSTL | | Aqua | FREE | \$0.00 | \$0.00 | | \$0.00 |
| 8 | | | | | | | | | |
| 9 | | | | | | | | | |
| 10 | | | | | | | | | |
| 12 | | | | | | | | | |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 16 | | | | | | | | | |
| Total: | | | | | | | | | \$58.41 |

Table 5. An itemized Bill of Materials for our design project

Technical drawing of a Central Harness Section showing three views: front, top, and side. The front view shows a rectangular block with a central slot and a dimension of 1.00. The top view shows a circular cross-section with a diameter of 1.00 and a width of 1.00. The side view shows a rectangular block with a central slot and a dimension of 1.00. The drawing is labeled "Central Harness Section - Inches" and includes a title block with fields for DATE, CHECKED, DESIGNED, DRAWN, and REVISED.

| | | | |
|----------|-----------|----------------------------------|---------------------------|
| DATE | 12/6/2015 | TITLE | |
| CHECKED | | Central Harness Section - Inches | |
| DESIGNED | | SIZE | REV |
| DRAWN | | C | Central Harness Section 2 |
| REVISED | | SCALE | 1/8" = 1" |

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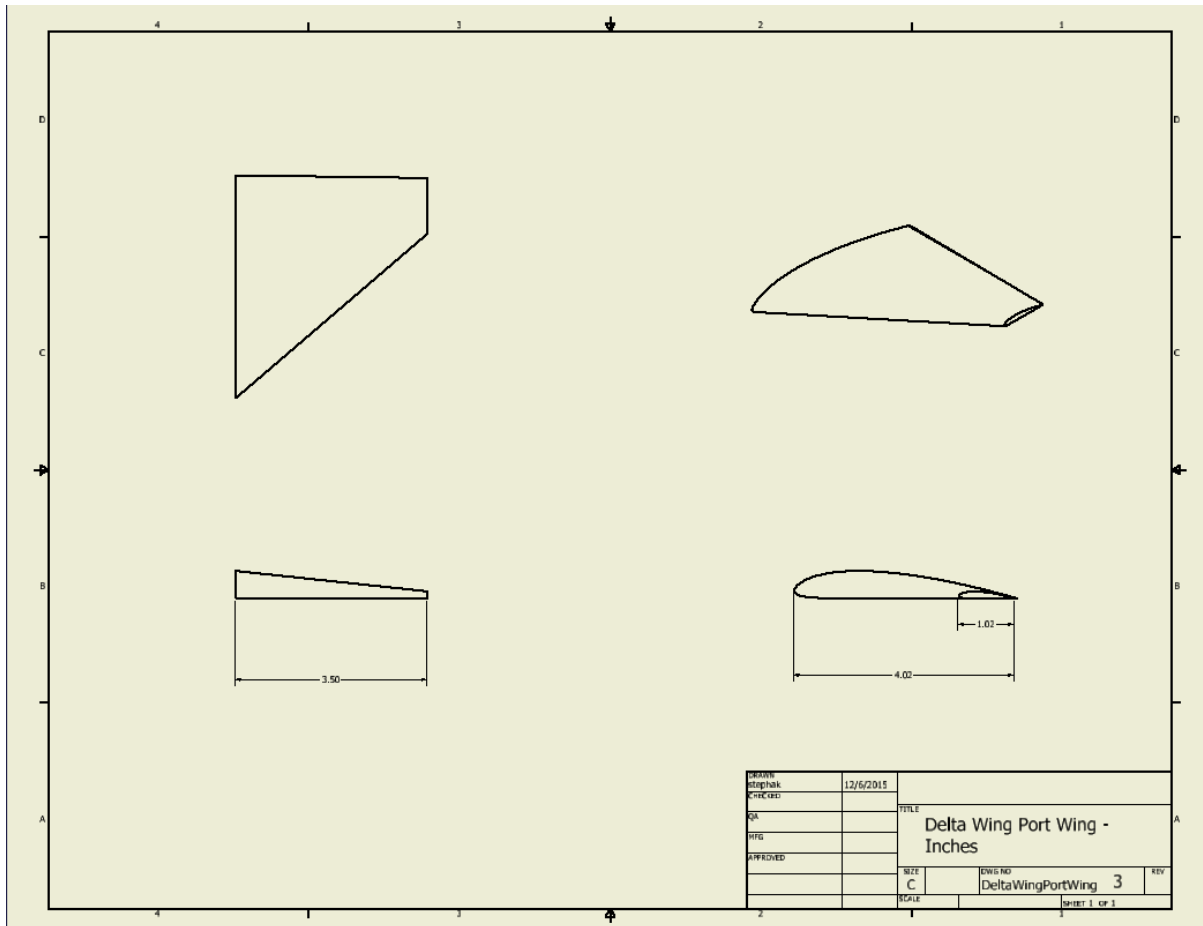


Figure 7. CAD Drawing of port side wing showing N-22 airfoil section

4.4 Description of the design rationale for the choice/size/shape of each part

The main constraint on the size of our parts was the 12" span limitation of Wash U's Fluid Mechanics Laboratory wind tunnel. To avoid wall interference, we limited ourselves to a span of 8", resulting in the dimensions seen above. We also knew by this point in our work that 8" mannequins that approximated the human form quite well were available to us. This worked to achieve the 1:1 span-to-height ratio that we observed in all modern wingsuits. Shape-wise, as seen above in our concept selection documentation, we found that the delta wing solved the problem of sudden stall sometimes suffered by elliptical wings, and allows a higher rate of speed during the jump, which in turn improves lift. The swept design increases aerodynamic efficiency (and decreases likelihood of a stall) but reduces the aspect ratio of the wing, which lowers lift coefficient significantly.

4.5 Gantt chart

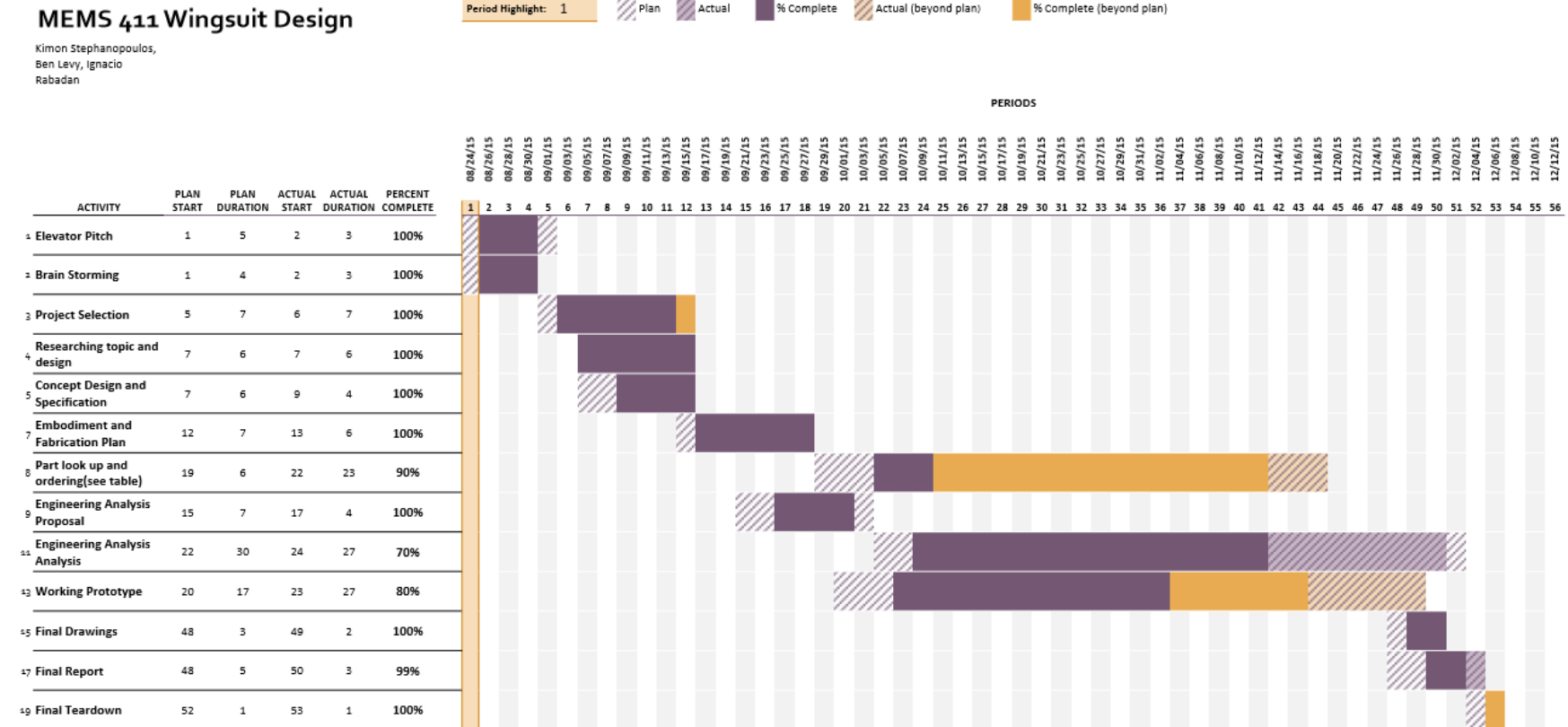


Figure 8. GANTT Chart describing our project's timeline

5 Engineering analysis

5.1 Engineering analysis proposal

The following engineering analysis tasks will be performed:

Before the prototype is built, we will need to conduct a rigorous analysis of various CAD models to determine a ballpark of wing sizes and weights. Our materials will be limited to what is available in the 3D printing facility. This will be simpler, as this part of the design is open-ended. More specific tasks to be completed pre-prototype include:

- CFD Aerodynamic analysis of 3D wings for wing shape considerations
 - Coefficient of Lift, Drag, Quarter-Chord Moment
- CFD analysis of 2D Airfoil shapes for lift performance optimization with minimal flow separation/assessment of stall performance
- Calculation of loads on wing for harness considerations
- Estimation of glide path for current wingsuits to determine proper speed & angle of attack for eventual wind tunnel testing
- Determination of optimal model size based on testing constraints TBD from communication with SLU Aerospace Chair (in progress)

Post-prototype, our analysis will be used to confirm the data we gathered before physical testing. Specific tasks include:

- Wind tunnel testing for lift and drag
- Final weight measurement/dimensioning to scale up for good correspondence with a full-size pilot
- Determination of glide ratio based on lift/drag performance to compare with current suits

The work will be divided among the group members in the following way:

- CFD work will be briefly run down by Kimon who will then delegate various wing models/airfoil sections to Ben or Ignacio for completion by the end of October
- Engineering calculations will be done in a group work session which should not require more than 3-4 hours to complete
- Determination of model size will be conducted by Kimon in liaison with SLU Aerospace Chair (contact information provided by Swami Karunamoorthy)

5.2 Engineering analysis results

5.2.1 Motivation. Describe why/how the before analysis is the most important thing to study at this time. How does it facilitate carrying the project forward?

The before analysis, especially the CFD testing, is expected to inform our wing design decisions and hopefully validate our choice of airfoil and wing planform as a high-lift, low-drag setup. Determination of optimal model size is most critical, as it will move us one step closer to manufacturing based on printer dimensions and test section availability. Calculation of the lift force for harness considerations and an estimation of the glide path taken by current wing suits are less important but would be interesting parameters to add to our final result. Certainly there are minimal harness strength considerations for our 8-inch wingsuit (especially considering our dummy pilot will likely be attached with glue), and the glide path is fairly simple to estimate from empirical evidence already available.

5.2.2 Summary statement of analysis done. Summarize, with some type of readable graphic, the engineering analysis done and the relevant engineering equations

Based on a review of several airfoil shapes, we came to the conclusion that the most effective airfoil to use for our purposes was the flat-bottomed N-22 airfoil shown in schematic form below. The reasons for this are twofold: Firstly, the airfoil's flat bottom seemed to ease manufacturing difficulties stemming from our 3D printer's inability to print on a curved base, and secondly, the same flat bottom meant we reduced the danger of creating an extremely high-pressure zone underneath the wing, moving our system closer to stall.

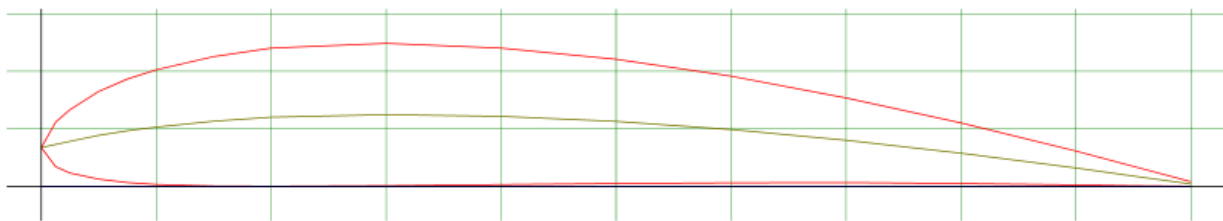


Figure 9. A graph of our chosen airfoil, the N-22, at a representative length of 1

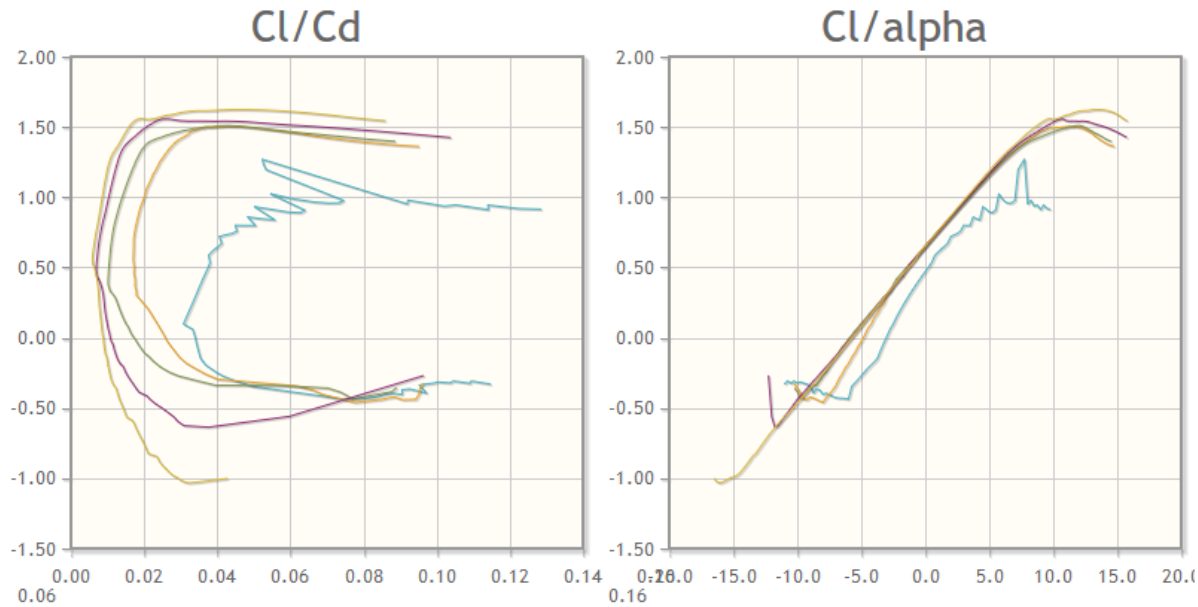


Figure 10. Plots of Cl/Cd and Cl/α for our chosen airfoil, the N-22

The goal of the added rigid wing is to improve the lift/drag ratio of the suit. To select the ideal planform, then, we must find the lift and drag coefficients for each proposed wing to optimize the wing for the suit.

To do so, we used SolidWorks to perform a CFD analysis of the wing. This gave us graphs comparing the lift and drag coefficients. The wings were initially designed in Autodesk Inventor using airfoils chosen from an online database. Then the wing designs were imported into SolidWorks to perform a CFD analysis. From the two wings designs we started with we were able to determine the better wing, and start building a model.

5.2.3 Methodology. How, exactly, did you get the analysis done? Was any experimentation required? Did you have to build any type of test rig? Was computation used?

The Computational Fluid Dynamics suite used was that included in Dassault Solidworks software. The difficulty of importing our model into ANSYS FLUENT and developing a suitable mesh for high-angle of attack subsonic flow visualization precluded our group from using this software. Extensive plots of lift against drag and lift against angle of attack for all airfoils we were deciding between were available on airfoil database websites such as AirfoilDB and Airfoil Tools.

To find the lift and drag coefficients, we used SolidWorks to perform a CFD analysis of the wing. This will give a graph comparing the lift and drag coefficients. The wings were initially designed in Inventor using airfoils chosen from an online database. Then the wing designs were imported into SolidWorks to perform a CFD analysis. From the two wings designs we started with we were able to determine the better wing, and start building a model. To test the model, which is a better

representation of the actual design, we used a wind tunnel to get the same types of values we got from the CFD solver. The main difference between the physical model and CAD models is the addition of the “pilot” dummy and fabric wingsuit.

5.2.4 Results. What are the results of your analysis study? Do the results make sense?

The results of the CFD analysis of the wings allowed us to pick which wing shape is better suited to our needs. The Delta wing had much lower drag than the Tapered wing and also had more lift. Lower drag makes more sense for a delta wing, and the higher lift is likely because of the greater surface area. The delta wing has a much higher lift to drag ratio, so we ultimately chose the delta wing.

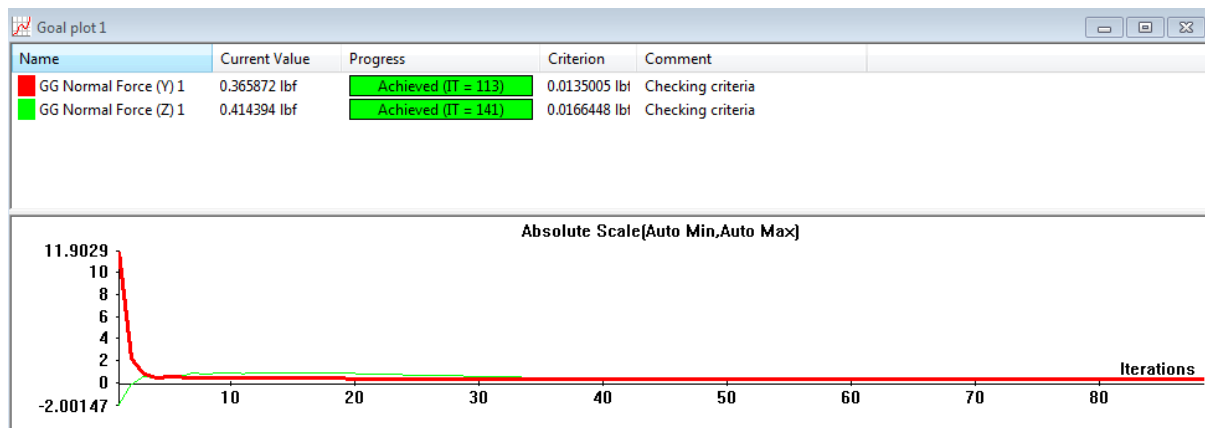


Figure 11. Solidworks CFD Results for the initial tapered wing prototype

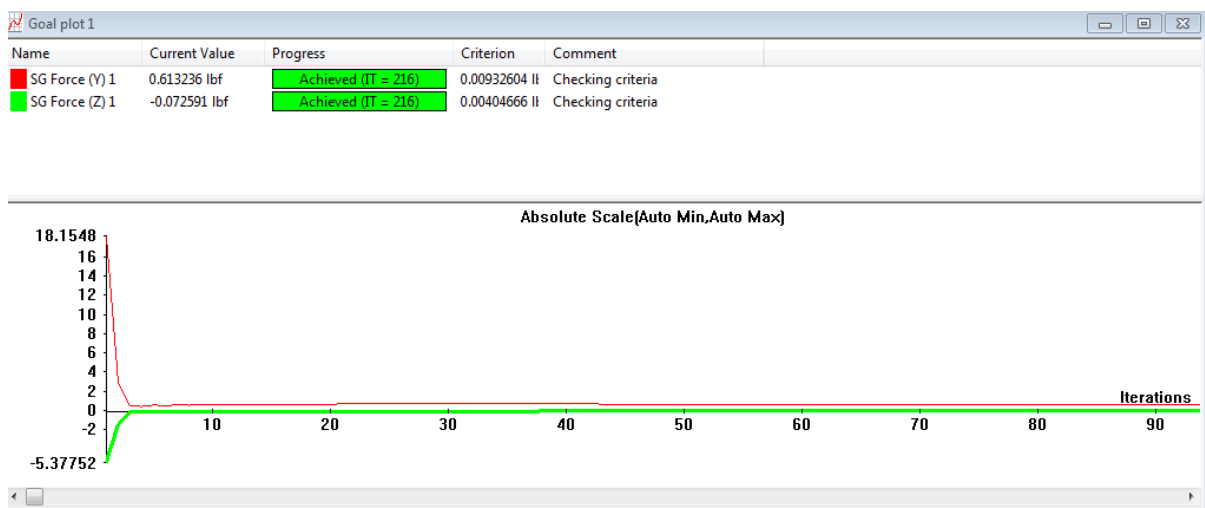


Figure 12. Solidworks CFD Results for the final delta wing prototype

We did however encounter some issues when running the CFD analysis. SolidWorks is not designed for complex shapes like wings, and is not a strong CFD program. It also had a tendency to crash. For example, the delta wing had a negative drag, which is not possible, and the tapered wing had almost equivalent lift and drag, which is highly unlikely. Because of these issues, the results from Solidworks are likely very inaccurate.

5.2.5 Significance. How will the results influence the final prototype? What dimensions and material choices will be affected? This should be shown with some type of revised embodiment drawing. Ideally, you would show a “before/after” analysis pair of embodiment drawings.

The main changes to the final prototype resulting from the pre-prototyping engineering analysis were an adjustment of the wing planform we chose to fabricate in favor of the delta wing. Note that our embodiment drawing above differs from the manufactured parts in the section after it – this change stemmed from careful analysis of the CFD results and the discovery that they were flatly in favor of the delta wing.

5.3 Risk Assessment

5.3.1 Risk Identification

The original scope of the project – a test of a full-size wingsuit on a crash test dummy of some sort – carried with it significant organizational as well as physical risk. It was obviously inadvisable that any group member (or any person, really) attempt to test our suit, so this was a non-starter. Such a project would have carried with it ridiculous levels of risk.

Even the scaled down project led to levels of risk, though certainly not physical risk as before. The primary risk was that data obtained from an 8” span 3D printed wing in a wind tunnel would not translate well to a full-size wing worn by a person in freefall. This is a high-level risk that can be mitigated by robust dimensional similitude analysis.

A second, and only slightly less important, risk was that we were unsure of what resources we had to complete the project. It was initially believed that the wind tunnel in Wash U’s Fluid Mechanics Laboratory was not set up for use yet. SLU Aerospace was slow to respond and ended up conducting maintenance on their tunnel until early November. It was fortunate that we could get in the wind tunnel in the Fluid Mechanics Lab, however it proved to not have been calibrated for data acquisition (one hypothesis for why we didn’t get readings from the balance).

A final, and the most minor, risk was choosing a project with a distinct lack of mechanical complexity to complete a Senior Design course for a Mechanical Engineering curriculum. There were projects offered that would have allowed us to demonstrate our mechanical design capabilities in a more straightforward fashion, but we took a risk in taking on a project that centered on aerodynamic design for experiment rather than this.

6 Working prototype

- 6.1 A preliminary demonstration of the working prototype (this section may be left blank).
- 6.2 A final demonstration of the working prototype (this section may be left blank).
- 6.3 At least two digital photographs showing the prototype

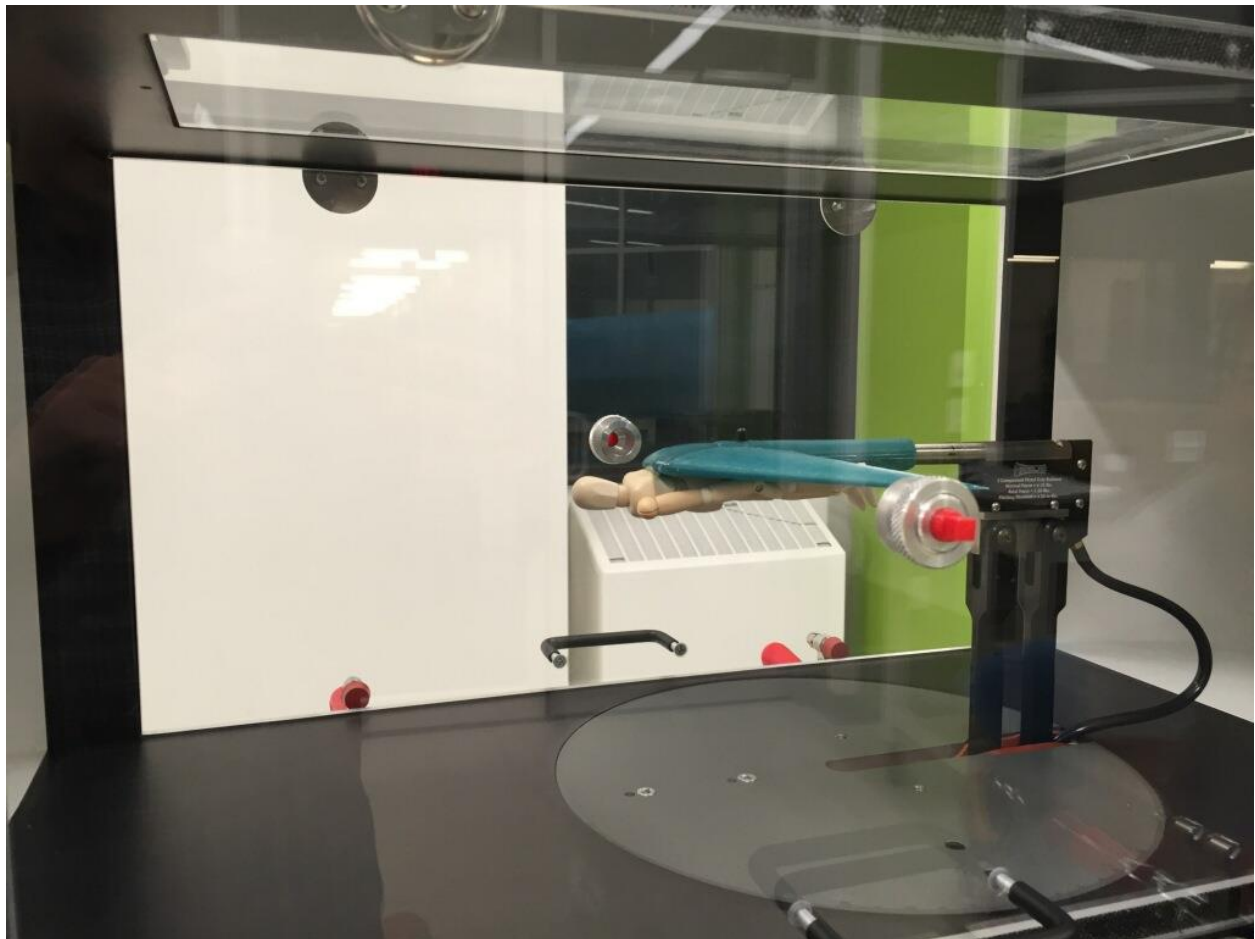


Figure 13. A side view of our prototype mounted on the wind tunnel testing balance

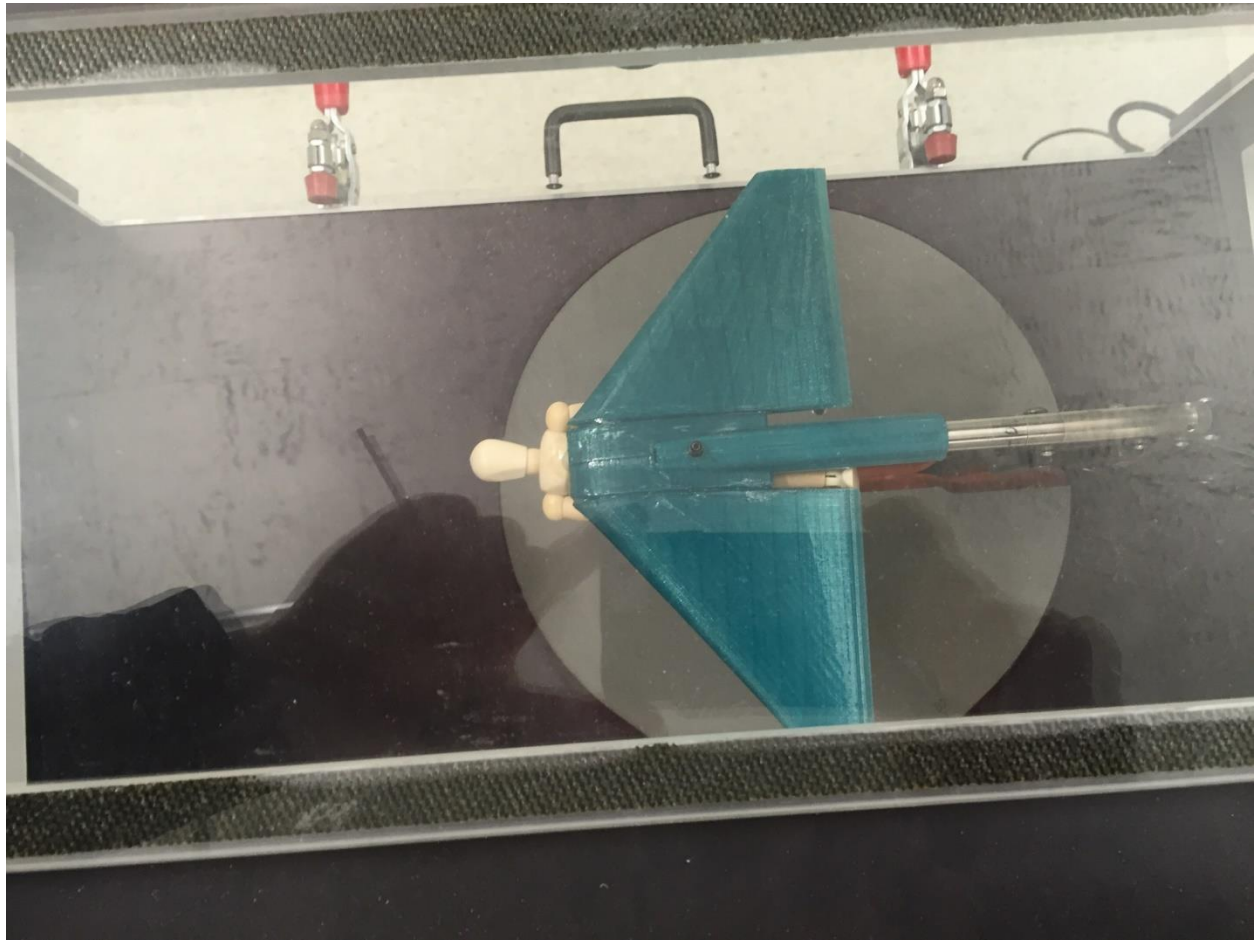


Figure 14. A top view of our prototype mounted on the wind tunnel testing balance

6.4 A short video clip that shows the final prototype performing

A short video of our prototype performing can be found at <https://www.youtube.com/watch?v=TaHFYyvtroI>.

6.5 Additional digital photographs and their explanations



Figure 15. A shot of the wind tunnel test setup in the WUSTL Fluid Mechanics Laboratory

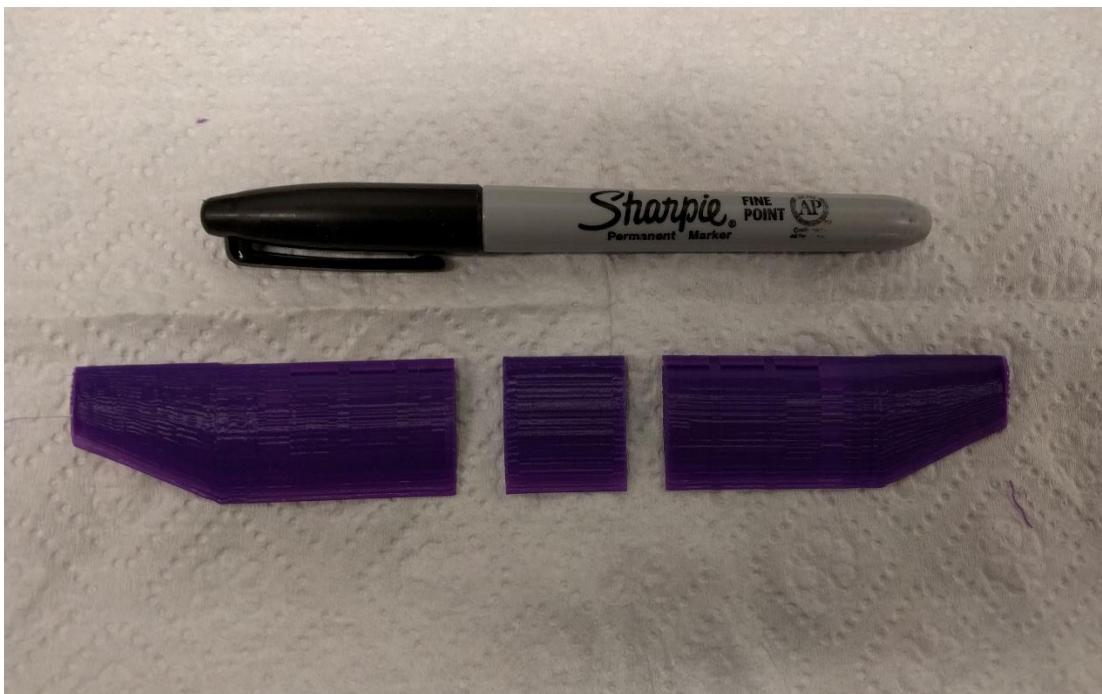


Figure 16. An initial small-scale print of a stall-resistant rectangular wing design

7 Design documentation

7.1 Final Drawings and Documentation

7.1.1 A set of engineering drawings that includes all CAD model files and all drawings derived from CAD models. *Include units on all CAD drawings.* See Appendix C for the CAD models.

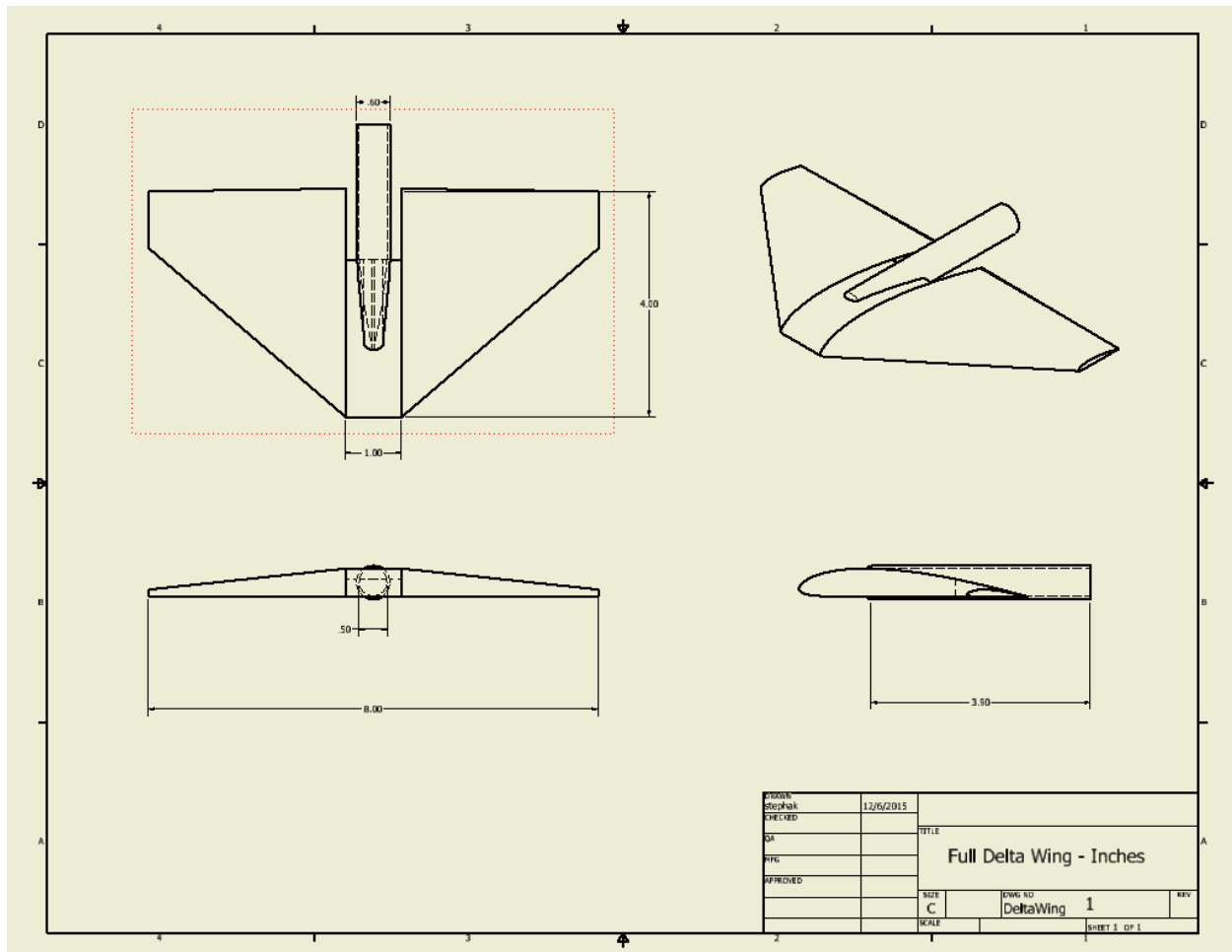


Figure 17. A final embodiment drawing of our delta wing design

7.2 Final Presentation

7.2.1 A live presentation in front of the entire class and the instructors (this section may be left blank)

7.2.2 A link to a video clip version of 1

The link provided is a video of the final presentation as given in class. The video may be cut slightly short because the recorder ran out of memory at the end.

<https://youtu.be/k9n5beaLXJI>

8 Discussion

8.1 Using the final prototype produced to obtain values for metrics, evaluate the quantified needs equations for the design. How well were the needs met? Discuss the result.

The main frustration of our project was that we were never able to assess whether our prototype design met the most important needs enumerated above. The complete lack of knowledge on how to use the wind tunnel data acquisition system proved to be an insurmountable hurdle for us. As such, we had no result to speak of, an unspeakable frustration for all of our groupmates, and, we are sure, the class, excited to see the culmination of one of the first scientific studies of wingsuit flight.

8.2 Discuss any significant parts sourcing issues? Did it make sense to scrounge parts? Did any vendor have an unreasonably long part delivery time? What would be your recommendations for future projects?

We had no issue getting most parts. The one frustration was that of finding an 8" mannequin to achieve the 1:1 span-to-pilot height ratio we were aiming for. Somehow, after placing two orders for 8" mannequins, we ended up with one 5.5" mannequin. This would have affected our data significantly, had we been able to get any. It is recommended that future studies attempt to approximate this 1:1 ratio more closely. The wooden mannequins allow for easy repeatability of the human form factor in these aerodynamic tests, and it is essential that they reflect the proportions of the pilot correctly.

8.3 Discuss the overall experience:

8.3.1 Was the project more or less difficult than you had expected?

The project was more difficult than we thought it would be but not for the reasons we expected.

The goal was to design a rigid wing, which we accomplished, but we were unable to test the design in any way.

8.3.2 Does your final project result align with the project description?

There is no way of knowing what kind of lift our scaled model produced in wind tunnel conditions, due to the unfortunate fact that no team member could properly set up the tunnel balance for testing (resulting in the problems with massive noise from the balance described above). In addition, no faculty was available to iron out the kinks. Data from similar studies conducted at high-level institutions indicate that there is more lift to be had in wingsuit design. We were unable to confirm whether we achieved this.

8.3.3 Did your team function well as a group?

Our team functioned very well. Everybody contributed and we had very few conflicts.

8.3.4 Were your team member's skills complementary? Did your team share the workload equally?

Each team member brought something different to the table that helped us achieve our goal. Kimon's sound knowledge of the underlying aerodynamics kept us focused, Ben's skills in the machine shop made rapid modifications easy, and Ignacio kept us organized and bought all of the parts not scrounged from the machine shop.

8.3.5 Was any needed skill missing from the group?

It would have been useful to have someone who knew more about 3D printing (in particular, printing with supports) and someone who knew how to use the wind tunnel. We were, so to speak, flying blind in the wind tunnel, without anyone who had an idea of how the data acquisition system worked.

8.3.6 Did you have to consult with your customer during the process, or did you work to the original design brief?

Given that our original brief was so open-ended, we consulted the customer throughout the process to better define the user needs as we designed the product. Our goals did not stray far from the originally pursued high-lift wingsuit as explained in the early sections of the report.

8.3.7 Did the design brief (as provided by the customer) seem to change during the process?

We changed our designs to accommodate the testing apparatus but the design brief and user needs never changed.

8.3.8 Has the project enhanced your design skills?

Yes. Through the project we learned we have to define what we are doing and determine the testing procedure early in the design process. We spent too much time on this and it limited the rest of the project.

8.3.9 Would you now feel more comfortable accepting a design project assignment at a job?

Every member learned a lot about the design process, in particular about the constraints on rapid prototyping and the necessity to boil projects down to the basics. We would all now be more comfortable accepting such a project at a job.

8.3.10 Are there projects that you would attempt now that you would not attempt before?

This project was a great introduction to aerodynamic design experiments, design for rapid manufacturing and design of experiments, and will definitely make future projects along those lines easier, in both the organizational sense and the designs themselves.

9 Appendix A - Parts List

See table 5 in section 4.2

10 Appendix B - Bill of Materials

See table 5 in section 4.2

11 Appendix C - CAD Models

See figure 17 section 7.1

12 Annotated Bibliography (limited to 150 words per entry)

1. Karl Nyberg--12/01507--S. *Flow Analysis of Apache Wingsuit* (n.d.): n. pag. Web. http://www.cd-adapco.com/sites/default/files/thesis/pdf/Examensarbete_Karl_Nyberg.pdf

CFD Study of High-Lift Wingsuit Flight + Assessment of High-AoA Stall in Same Suit:

2. Michael Berrya, Jonathan Las Fargeasa, Kim B. Blair, b, a Massachusetts Institute of Technology http://ac.els-cdn.com/S1877705810003139/1-s2.0-S1877705810003139-main.pdf?_tid=fba42c7c-5d4a-11e5-9c26-00000aabb0f02&acdnat=1442501413_8413e9aaced2b7ae7dd647a0c002c7a1

MIT Study of Redesigned Wingsuit w/ Airfoil Extending Past Head (with support of Phoenix-Fly and references from the same Aero textbook Ben and I used!): Determined that the extended suit created more lift but also more drag resulting in a long, slow flight. We would want to just have lift.

3. "Flying Without Dying: The Future of Wingsuit Design." *Behold the Infinite*. N.p., 04 June 2015. Web. 06 Dec. 2015. <https://beholdtheinfinite.wordpress.com/2015/06/04/flying-without-dying-the-future-of-wingsuit-design/>

Some kid's Tech Writing final paper which happens to be a great summary of past wingsuit designs and assessment of the foreseeable future, including great references:

4. <http://commons.erau.edu/cgi/viewcontent.cgi?article=1168&context=aircon>

Awesome study from Embry-Riddle that aligns with our thinking that current wingsuit materials are straight up bad for flying (while the object of the study is to optimize the wind tunnel itself):

5. "Aerodynamic Design Of A Wingsuit" Y. Segev, E. Yablochkin, Y. Green, L. Mintz, O. Neeman and R. Levin <http://aerospace.technion.ac.il/projects/aerodynamic-design-of-a-wingsuit/>

This article explains the goals for the future of wingsuit design, and their opinions on what it should be. A study testing current wingsuit designs that lead to the conclusion that range and endurance can be improved. Also mentions force on limbs and handling

This was a project much like ours, but unfortunately it seems the kids at the Technion had access to bigger and better wind tunnels... Let's see if we can get access to the study itself.

6. Indian Journal Of Fibre & Textile Research, and December 2011 Pp. 327-335 Vol.36. Design and Engineering of Functional Clothing (n.d.): n. pag. Web. [http://nopr.niscair.res.in/bitstream/123456789/13226/1/IJFTR%2036\(4\)%20327-335.pdf](http://nopr.niscair.res.in/bitstream/123456789/13226/1/IJFTR%2036(4)%20327-335.pdf)

Design and engineering of functional clothing→Talks about the strengths of different fabrics and the conditions under which they are useful/bad.

